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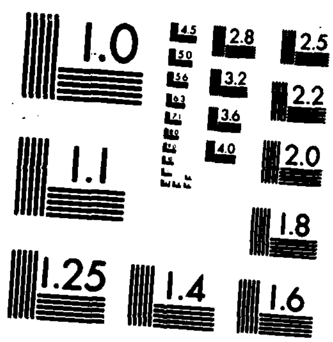

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Experimental Investigation
of the
Turbulence Production
Mechanism
in
Boundary Layers

by

R. E. Falco

Yearly Report

Prepared from work done under
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Turbulence Structure Laboratory
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ABSTRACT

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1. INTRODUCTION AND REVIEW OF PROGRESS

A great deal of work is being done to try to control the onset and production of turbulence in boundary layers. However, only vague concepts about the structural features are understood, some of which are wrong, which has led to large scale efforts which don't have a firm foundation. The engineering devices such as LEBU's and riblets do change turbulence structure, but what they are doing is currently not understood (in spite of a lot of comments to the contrary). New ideas for control or management of turbulence in boundary layers based on an incorrect or incomplete view of the physics are likely to direct people and resources away from the critical path that will ultimately give us the information needed for a rational approach to control. It appears that fewer resources are being directed at continued understanding of the phenomena. Although the fundamental research path may appear to result in slow progress, I feel that it is real progress. Furthermore we are embarking upon a period where the use of photo-optical measuring techniques can accelerate our rate of understanding.

In what follows I will review our progress in understanding. In my research I am constantly alert to opportunities to control turbulence, and will outreach, doing control related experiments, when there is a identifiable mechanism to attempt to control.

1.1 Our five pronged attack on the turbulence production phenomena

We have been performing a five pronged attack to validate the theory put forth in a series of papers over the past several years, and to obtain new data about the causes of turbulence production near walls. In the course of this period's work new data enabled us to enhance the theory to include all of the important facts. These are described below after a brief review of the essentials of the revised theory. The five prongs are: multiple probe array/simultaneous flow visualization experiments in a thick boundary layer in air; laser sheet/flood light visualization to determine the inner/outer layer interactions; multiple color fluorescent dye marking experiments in water; vortex ring/moving belt simulations in water and kerosene; and vortex ring moving riblet plate experiments in water.

1.2 Review of the revised structural theory

The theory has reached a new level of completeness and unification because we have discovered that all of the sublayer perturbations and structural components can be caused by Typical eddies convecting over the wall. The theory says that the major transport occurring in the turbulent boundary layer is brought about by three structural features: the large scale motions, the Typical eddies and the local instantaneous thickness of the sublayer. These features can be used to model essentially all of the events that have been observed. The one exception was the formation of the long streaky structure in the wall region. Our new observations have filled this gap.

The key new insight developed as a result of measuring the convection velocity of Typical eddies at various positions across the boundary layer and finding that a large number of them were moving at essentially the local mean velocity of their center of mass. For these eddies, we were talking about .7 U_{inf} or greater. Up to this time we had been following the suggestion of Emmerling, Eckelmann, and others who noted that the pressure producing eddies convected at speeds as low as .2 U_{inf}. A further weak point of the simulation that formed the basis of our model was our association of the edge of the Stokes layer with the edge of the viscous sublayer. Thus, in our simple Galilean transformation, we assumed that $U_r/U_w = 1 - .5\ U_c/U_{inf}$. As a result, our simulations modeled Typical eddies that moved $0 < U_{inf} < .5$, whereas our new measurements show that the majority of the Typical eddies are moving faster. The faster moving eddies exert an influence on the wall from a greater distance than we had previously witnessed. They also result in a far field interaction that produces pairs of the long streaks. Investigators have been observing similar streaks since the early studies of Hama and Kline. The fact that interactions can take place at a greater distance from the wall, allows a greater number of eddies to be involved. In Part II (A report of work in progress), we describe the experiments that provided the new data. Because of the need to have high resolution to define details of the local interactions as well as encompass the long distance interactions, a number of different techniques had to be used. In what follows we summarize the emerging overall picture.

Typical eddies, which are Taylor microscale size vortex rings, are created by vorticity redistribution in the outer layers near the upstream side of the large scale motions, and by pinch-off of lifted hairpin vortices. While both of these processes have been observed, in a) the fully turbulent boundary layer, b) vortex ring/moving wall interaction experiments, and c) full Navier-Stokes calculations (Moin, Leonard and Kim, Phy Fluids April 1986), they are not yet fully understood, and experiments are proposed below to gain an understanding. It is in modifying these processes that we have the greatest chance of controlling boundary layer turbulence. The Typical eddies are convected over the wall in the speed range of $.2 < U_{inf} < .95$, but most of them move faster than $.7\ U_{inf}$. We will, at this point, define a fast Typical eddy, somewhat arbitrarily, as one moving with $U_c > .7\ U_{inf}$. When we investigated the interactions possible with the faster eddies in our vortex ring/wall simulations, we immediately witnessed the other aspect of the turbulence production problem, i.e., the appearance of long streaks and their breakup. This is the aspect most other investigators have concentrated upon. Thus, we now have in one structural model the two most important features of the production of turbulence. Previously it had appeared that two different mechanisms would be required, but only one is seen to be needed: the Typical eddy wall interaction. The high speed Typical eddies cause a rearrangement of the wall layer fluid into streaks that are spaced approximately the diameter of the eddy. Since the distribution of eddy sizes is lognormal, with its mean around 100 wall layer units in low Reynolds number boundary layers, we immediately have the basis for the streaky structure scaling. The Navier-Stokes equations indicate that we can generate streamwise vorticity near a wall by the presence of a spanwise pressure gradient. Thus, we do not need the pre-existence of streamwise vortices in the model. This certainly removes one of the sources of mystery from the boundary layer. Thus it is clear for a given δ/D as we cover the range of convection velocities we can uncover the range of interactions the coherent outer layer motion can cause.

Additional measurements in the turbulent boundary layer indicated that zero degree angles were not uncommon and that some Typical eddies had negative angles (they were moving away from the wall) while the interactions were observed.

If the Typical eddy is in the correct speed range to produce streaks, then the absolute distance from the wall, the thickness of the wall layer, the eddy size, and the angle of incidence determine the ensuing $stability$ of the streaks that are formed. All other parameters held constant, if the eddy is moving parallel to the wall and its distance is greater than some critical value, long stable streaks are created. If its distance is less, a pair of streaks starts to form, but it never stabilizes, and is observed to immediately become unstable, with the initial steak pair bifurcating several times into additional streaks, which all undergo wavy breakdown, and quickly leave the appearance of a turbulent spot forming in the wall region. This process, which has not been observed before to my knowledge, depends upon the Typical eddies' speed, size, distance from the wall region, and the thickness of the wall layer. Experiments have shown that $h_1/\delta < 3.5$ for a visually detected interaction, where δ is the edge of the viscous region or $y^+ = 30$.

The role of the thickness of the sublayer must be reassessed again in the light of the new range of findings.

We have observed that the time to breakup of the long streaks that do so is longer in thicker wall layers. Furthermore, the mode of breakup is different. In a thin layer the streaks break up by undergoing a growing waviness: in a thick layer by a mechanism of lumping up and having hairpins form on them (proposed by Smith, and one of the two type of breakdown seen by Blackwelder and Swearington in their streaks generated by Taylor-Gortler vortices, although it was their least likely mode of instability).

The size and the angle of incidence of the Typical eddy are important parameters determining the nature of the interaction. An interesting fact is that under constant ambient conditions, for eddies of shallow angle, there is also a critical $size$ above which the interaction is massively unstable, resulting in the 'spot' mentioned above. Just decreasing the size is sufficient for the streaks to form and remain stable. As the eddy gets closer to the wall, it creates a pocket, and may undergo the Type I, II, III, or IV interaction (reviewed below). The massive instability may be the most violent interaction to occur in the turbulent boundary layer. Falco 1977 (Phy Fluids 20, p 124) called interactions which had this character 'superbursts'. These are bursts that are considerably larger and involve finer scales within them, and occur one tenth as often. With our current understanding, it now appears that the distance from the wall is as important as the angle of incidence. Large scale inflows that can bring the Typical eddy close enough to the wall can cause interactions ranging from minor to a superburst. Thus, large scale motions play an even more critical role than previously thought, since it now appears that there is some critical distance from the wall which, if they can convect the eddy to, can result in strong vs. weak interactions. So, a change in the strength of large scale sweeps can keep a host of Typical eddies out of the interaction range.

Since the size of the Typical eddy is a function of the Reynolds number -- the Typical eddy decreases in size as the Reynolds number increases -- those interactions depending upon the absolute size will decrease in number and strength, while aspects depending upon the wall layer scaled size will increase. So, for example, the occurrence of superbursts may increase, and the spacing of streaks may also increase, or streaks may disappear altogether because conditions for their stability no longer exist. An understanding of how to non-dimensionalize the parameters of size, distance from the wall, and wall layer thickness needs to be gained.

It should be pointed out that the streak breakup does not appear to be a simple shear layer instability in the normal sense, which depends upon δ and the velocity difference. In simulations of streaks formed by vortex ring/wall interactions, we could keep the velocity difference the same, keep the shear layer thickness the same, but create streaks that were very stable vs. streaks that were immediately unstable by varying the size of the ring by an almost immeasurable amount.

A subset of Typical eddies which are in the range $h_1/\delta < 1.7 - 2.0$ and are moving very slowly, .2-.4 U_{inf} will form a hairpin vortex at the downstream end of the interaction region from which a streak pair was initiated, if the incidence angle is very shallow, and this hairpin can lift up and pinch-off, forming a new vortex ring/Typical eddy.

In general, however, the Typical eddies that move slower interact in a more local way. They do not produce the long streaks or the extensive wall layer breakup. Their disturbance is organized around the pocket footprint. Fast eddies, which exist farther out, will produce streaks and pockets, while the slower moving Typical eddies which are closer to the wall will produce only pockets.

We have also observed Typical eddies that clearly produce a Type II interaction which are more than one diameter from the wall, i.e., they produce large clear pockets and no streaks, and they remain stable and have a hairpin liftup from the pocket, which goes back down to the wall. These eddies are moving slowly so they represent fluid that has recently moved quite far from the wall, and/or formed a strong Typical eddy that is inducing itself in the upstream direction against the mean flow.

With our new information and understanding of the far field effects of the Typical eddy, it has become clear that we have a broader range of interaction producing turbulence that must be classified. The new classification is in the order of increasingly strong interaction: No interactions of any type occur if $h_1/\delta > 3.5$. We must now consider both the stability of the ring and the stability of the the streaks in all cases. We will organize the classification around Typical eddy speed. Organizing around speed, we can keep the four Types previously identified (and reviewed below), but need to add six additional, which involve the streaks, and the superburst.

The four types previously identified which involve local interactions all involve slow speed Typical eddies moving towards the wall:

Type I -- Interaction results in a pocket, which has a weak liftup at its downstream boundary which results from induction by the Typical eddy, that is confined to the wall layer ($y^+ < 30$). The eddy leaves the interaction intact. It results from very low speed TE moving at shallow angles, and the sublayer must be thick. The probability of this is very low primarily because of the low probability of an eddy having this speed.

Type II -- Interaction results in a pocket, which has a strong hairpin lift out of it downstream boundary as a result of induction by the Typical eddy. This hairpin moves beyond the wall layer. No fluid is ingested into the ring, which remains stable as it moves away from the wall. These interactions have been observed for eddies moving towards the wall at shallow angles.

Type III -- Eddy moves towards the wall, interacts creating a pocket. The hairpin liftup induced by the Typical eddy at the downstream boundary of the pocket is partially ingested by the eddy. This ingested fluid causes the eddy to become unstable and it breaks up as it moves away from the wall. The wall layer must be thin and vortex stretching, due to inviscid image effects, dominate the physics.

Type IV -- Interaction results in a pocket, and liftup induced by the Typical eddy, that is almost completely ingested into the eddy which is strongly stretched as it gets close to the wall in a thin wall layer. Both the eddy and the lifted ingested fluid breakup in the near wall region.

Non-local interactions resulting from Typical eddies convecting at speeds > .7 U_{inf}.

Type I(S)-IV(S) -- Typical eddy moving towards the wall at a shallow angle produces a pair of parallel streaks followed by a Type I - IV interaction as the eddy gets closer to the wall.A further breakdown is not possible at this stage. We need additional experiments to uncouple the dependence of the angle of incidence, and the various scales, to understand why at times the pair of streaks will be stable, and at other times they will become lumpy or wavy and breakdown. Clearly the angle of incidence is an important variable. We have further observed that the time to instability of those streaks that do become unstable is longer in a thicker wall layer.

Type V -- Typical eddy moves toward the wall at a shallow angle and starts to produce a pair of streaks. However, from their inception these streaks do not have a definable spacing, but continue to move apart, then they bifurcate, producing other incipient streak pairs that are also not stable. As the third pair is forming, the first pair is undergoing wavy breakdown; soon all the streaks are breaking down and include the pocket that forms by about the time of the first bifurcation. The overall breakdown strongly resembles the growth of a turbulent spot. This can occur with the Typical eddy undergoing a Type II to Type IV interaction. I do not feel that this event should be classified as a low speed streak pair instability, because streaks only begin to form and never attain a stable state from which to go unstable. The interaction should be looked upon as whole.

An additional type of interaction has been observed that does not classify according to eddy convection velocity.

Type VI -- Typical eddies moving at very shallow angles to the wall. If the convection velocity is <u>low</u> ranging from $.1 < U_{inf} < .4$, will induce a hairpin vortex of lifted fluid trailed by a pair of long, very stable streaks. If the angle is towards the wall the lifted hairpin has been observed to pinch-off and form a new vortex ring. If the angle is away from the wall the hairpin doesn't pinchoff. In this interaction a pocket may not form. The streaks are close together when the Typical eddy is far away, but moving towards the wall, and progressively spread if the eddy starts closer to the wall. This is a case where the effect of angle is greater than the effect of convection velocity. The probability of occurrence is relatively high because it represents the case where a Typical eddy is evolving from a hairpin that has lifted from the sublayer and has recently undergone pinchoff.Both the ring stability and the steak stability depend on the layer thickness, but the streaks first develop into long parallel pairs before any instability sets in.

As we can see, the importance of a thick sublayer in reducing the intensity of the turbulence production is clouded by the presence of these additional poorly understood interactions. It is, of course, still of great importance for slow moving eddies, but the faster moving eddies will make an important contribution to the momentum transferred by creating long streaks that may become unstable. We have two tasks before us. First, we must determine the frequency of occurrence of each of the types of interaction; and second, we need to determine the parameters that govern the stability of the different types. Determining the frequency of occurrence will require a number of different techniques of flow visualization, as discussed in the next section, but it is clear that some of the interaction types discussed above will not be frequent in low Reynolds number flows, although we suspect the situation at higher Reynolds numbers may well be different.

Determining the parameters governing the occurrence of a particular type of interaction in the fully turbulent boundary layer is very difficult because we need to measure all relevant parameters, in a environment where several interactions may be occurring at the same time. Our current procedure involves continuous observation of the turbulent boundary layer until those times in which essentially only one type of interaction is occurring in isolation. We then measure various parameters with hot-wire anemometers. We have, of course, been helped in an important synergistic manner by insights from our vortex ring/wall simulations. Experimentally, a major increase in our ability to determine the governing parameters will result from being able to quantitatively follow the evolving flow in two dimensions. Being able to make measurements as the flow evolves means that we will relax the constraint of exact phasing of the turbulence with our instruments. Furthermore, we will be able to measure quantities like the vorticity and strain-rate over a field, so as to understand questions of the sensitivity of interactions. This will essentially put our capability on a par with low Reynolds number NSE computational work in channel flows. It does not overcome the problem, common to both approaches, that in the boundary layer a number of production events, in different stages of their evolution, may have an effect on the measurement area at the same time. (We will have the advantage of larger ensembles, but more limited data, and the capability to increase Reynolds number, but I forsee a strong synergism developing between the two.) We have begun research in the current period to enable such measurements to be made.

A second important point is that it is now clear that making a 1-1 correspondence between all the streaks that form and coherent motions that exist in the flow above the wall is not possible. This is because of the streak instability mechanism that leads to bifurcation and breakup. Obviously, if a portion of a streak created by the bifurcating mechanism is in the streamwise/normal laser sheet, we would not find a Typical eddy or any other coherent motion above it (upstream or downstream).

The breakdown helps to point out that there are essentially two ensuing streak instability mechanisms, the wavy breakdown, and the lumpiness which evolves into hairpin vortices. The cases where streaks form and are initially stable, but then undergo rearrangement through lumpiness or wavy breakdown, do result in additional turbulence production, but it is weak, and I have characterized it as slow production, in contrast to the Type II-IV interactions or the Type V interaction. The existence of the streaky structure contributes to the production of turbulence in the following ways:

a) it lifts fluid away from the wall, bringing it into closer contact with the vortices further out, so they can induce continued outward motion;

b) the long streaks do become unstable in the lumpy mode, which slowly grow to form hairpin vortices which move away form the wall.

We have observed that this mode of instability occurs more often when the wall region is thick. It is my opinion that far too much has been made of the existence of these hairpins. Obviously, the structural picture presented here relegates them a secondary role.

c) they can become unstable by developing a growing wavy instability that amplifies and leads to a wispy fragmenting of the dye in the streak over a fairly long time scale (low production rate),

d) they locally thicken the sublayer, promoting weaker Type I and II interactions when new eddies interact over them,

e) their formation locally thins the sublayer in regions between the low speed streaks enhancing stronger interactions of Type III and IV, when new eddies interact over the high speed regions.

Finally, observations clearly show that in the low Reynolds number turbulent boundary layer there is a predominance of well defined pockets. This follows because in almost all the cases of interaction pockets are a part of the events. At times we have also observed several pockets in a row resulting from one Typical eddy.

1.3 Correspondence with full Navier Stokes calculations

During the course of this past year, two of the key observations that are fundamental to our picture of the turbulent boundary layer have been confirmed by supercomputer calculations performed at NASA AMES using the full Navier Stokes Equations (P. Moin, Bull. APSDFD 1985 p

1723; and Moin, Leonard and Kim, Phy Fluids 29 April 1986). The first correspondence shows that the pockets are the essential Reynolds stress producing event in the wall region. The second set of calculations have shown that vortex rings can be generated by two mechanisms present in turbulent boundary layers. The first is by 'pinchoff' of lifted hairpin vortices, and the second is by redistribution of diffuse vorticity at the upstream side of a large scale concentration of vorticity that resembles a large scale motion. The calculations, while confirming these underpinnings of our theory, can also be used to enhance our understanding of the physical circumstances that cause them.

1.4 Predictions based on the structural model

Two types of predictions arise out of the findings. One is that there is a Reynolds number dependence of the streaky structure. I am not only talking about the streak spacing, but I am more fundamentally referring to the existence of the long streaks. The other is that we should expect structural differences in channel flows.

1.4.1 Reynolds number dependence of the production process

At high Reynolds numbers, the Typical eddies increase in size with respect to the sublayer thickness (Falco 1977).Thus, the interactions that would result in stable streaks at low Reynolds numbers would cross the stability boundary, and would not form at higher Reynolds numbers. Thus, we would have a different picture of the balance of streaks and pockets at higher Reynolds numbers. In the extreme, at very high Reynolds numbers relevant to technologically important flows, we may not see long streaks at all.

The strength of the large scale motions also increases with Reynolds number. Therefore, the angle of incidence of the Typical eddies caused by the large scale wallward sweeps will be lower at low Reynolds. Our simulation experiments show that, other conditions held constant, if the angle is reduced, more long, stable streaks will form. Thus, we expect that at higher Reynolds numbers, fewer streaks will form. Thus, we expect that the streaks will not be a significant part of the wall layer structure at high Reynolds numbers.

Recently, Smith (1983) extended streak spacing measurements to $R_\theta = 5830$, and concluded that the spanwise distribution of the streaky structure did not change appreciably, and that the appearance was essentially the same. He suggested that this would be the case for higher Reynolds number flows. However, Hydrogen bubbles only give visual information in the region close to the bubble wire, and thus, the observer can't tell whether he is observing long streaks or short streaks. Short streaks are developed along the sides of the pockets, and are the order of 100 x^+, so appear exactly as the longer streaks in Hydrogen bubble experiments.

1.4.2 Channel flow differences

The second prediction concerns the difference between channel flows and boundary layer flows. For many years it has been observed that the burst rate indicators in channel flows give different results from those in boundary layers. Because of the flatter 1/7 power profile, the convection velocity of the Typical eddies will be higher, and it is furthermore the case that the angle of incidence is flatter, because the large scale sweeps are not a strong as in a boundary layer. Therefore, the likelihood of Typical eddies creating stable streaks should be greater in a channel than in a boundary layer.

2. REPORT OF WORK IN PROGRESS

Progress has been made in all five areas of investigation. Although we have had our best year yet in terms of discovery and verification of our ideas by others, we have had a slow year building the convergent statistical ensembles needed. First we had a large turnover. Both Liang and Shyr graduated with the MS degree and left, and Zabdawi, Klewicki and Chang had to study for their PhD qualifiers. Zabdawi failed and took a research assistant position at Univ of Toledo, Klewicki passed, and Chang passed 2 of 4 and needs to take the remaining in September. Zabdawi was replaced by Oldeweme. Furthermore, Zoran Zaric tragically died in December, bringing the detection work to a crawl. During most of this period, the Copper Vapor laser, which plays an important role in our work, has been marginally operational (it has recently been completely overhauled in California, and we now understand that its upkeep will be costly). Finally, we have had a difficult time with the Data Translation simultaneous sample and hold A/D and its software. Nine months of calls and mailing to the English software house before the bugs were worked out have made its initially inexpensive price a bad choice.

2.1 The five synergistic research projects

The five prongs are complementary attacks on the problem of understanding turbulence production. We have found that advances in our hypotheses have required us to go back and forth examining data obtained from the different techniques available in the laboratory, as well as have the capability to choose the technique that is best when new data is needed to answer specific questions that arise.

2.1.1 Multiple probe array/simultaneous flow visualization

The multiple probe array and simultaneous laser sheet flow visualization experiment is aimed at quantifying the phase relationship between the large scale motions and the vortex ring-like Typical eddies, and determining the importance of the sublayer thickness in the production of turbulence. Joe Klewicki is the graduate student running this experiment.Here, we are looking for several pieces of information: a) the strength of the large scale sweep necessary to move a given strength Typical eddy towards the wall; b)the strength of a Typical eddy necessary to produce a liftup of wall layer fluid; c) the relationship between the convection velocity of the Typical eddy and its strength (we will measure vorticity and Reynolds stress); and d) the relationship between the thickness of the sublayer and the severity of the interaction. In general, we are interested to determine if the actual boundary layer events have the same stability characteristics as vortex ring/wall simulation. This experiment has not yet been successfully performed primarily because of sequential failures of one or another system, i.e., laser, A/D, computer, and because of the difficulty keeping all wires calibrated and not broken in the oil fog environment. We do expect our first successful run this summer.

2.1.2 New visualization of the inner/outer layer interactions

Both 16mm and 35mm movies have been made of the visualized turbulent boundary layer at low Reynolds numbers.

2.1.2.1 Pocket as wall phenomena

A number of experiments using artificially generated hairpin vortices have suggested that the pockets observed by myself and others are structures that exist well out into the boundary layer, and are thus, by implication, not the wall phenomena suggested, but simply the visual pattern one would see under the legs of a tilted hairpin vortex. We wanted to show that the influence actually extended into the sublayer and to the wall. This was demonstrated by the following experiment: A surface with very low shear modulus, and very low damping was installed in a kerosene flow channel. Because of the index of refraction of kerosene over Gelatin (which is a protein matrix holding a large percentage of water), we were able to easily observe very small deflections in the surface before the onset of wave motions. The deflections had the shape, scale and the frequency of occurrence of pockets, confirming our understanding.

2.1.2.2 Smoke washout technique using a single laser sheet parallel to the wall, and two mutually perpendicular laser sheets

This old technique has been used with a new twist; the washout is observed only in the confines of a laser sheet that is parallel to the wall and extends from the wall to about $y^+ = 15$. *The* laser sheet focuses attention on the wall for the entire field of view, whereas slit marking/flood illumination soon masks the wall, because the marker is convected away from the wall, obscuring the wall events. We found that the long streaks would last a very long time on average, suggesting that the near wall region of the streak is not involved in the breakup. We also found that pairs of streaks could be observed to evolve, which sometimes had a pocket form at their downstream end.

Using two mutually orthogonal laser sheets, we found that Typical eddies which where quite distant from the wall (distances greater than their diameter) could create a hairpin lift-up at the wall. If they convected essentially parallel to the wall, or moved outward, they produced a pair of long streaks which were quite stable as viewed in the laser sheet parallel to the wall. These interactions did not result in a pocket forming. These eddies were on average moving at speeds close to the local mean velocity, putting them in a range $.7 < U_c/U_{inf} < .9$. Typical eddies that were also as far from the wall, but which moved towards the wall, could also be seen to produce pairs of long streaks. However, these culminated as the eddy came closest to the wall by forming a pocket, which opened up at the downstream boundary of the streak pair. When the pocket formed the streaks were more often unstable.

Isolation of the parameters involved was only possible in the vortex ring/wall interaction simulation experiments, which were used to determine the sensitivity of parameters involved in these streak formation events.

Although the laser sheet/smoke washout technique is very informative, it can't be used to build up significant sample sizes, because each experiment reveals information for only the very brief period during which the marker goes from high to zero concentration. In practice this has meant data over about two boundary layer thicknesses. Thus, the odds of catching the events of interest in the two laser sheets during this short time is low, and thus an impractically large number of experiments would be needed.

We have, instead, started a different approach, using fluorescent dyes and multiple sublayer slits in a water tunnel, which is described below.

Another new aspect of the interaction was observed in these movies. We found that a single Typical eddy could produce more than one pocket. This occurred when the eddy was on a shallow wallward trajectory, from which it created a pair of long streaks, with two (sometimes indication of three) pockets which were roughly in line between the streaks at their downstream end. The formation of the pockets, with their hairpin lift-up, marked the culmination of the interaction. No additional wall disturbance was noted downstream.

2.1.2.3 Dual slit laser/flood light visualization of boundary layer in two mutually orthogonal planes

New results using this technique, where we had a field of view that covered the entire boundary layer, with smoke emitted from one slit far upstream filling the entire boundary layer, and a second slit in our field of view, helped to confirm the above findings, but whereas the washout technique allowed streaks to be seen most clearly, the slit enabled us to view pockets most clearly. With this experiment we focused on trying to build up a larger sample of events, with clearer information about the typical eddy/wall interaction. However, the question of whether Typical eddies have caused the long steaks can't be determined by this technique, because we don't have information upstream of the slit, and the lifted fluid quickly 'clouds up' the picture downstream.

2.1.2.4 Majority of the interactions at $R_\theta \cong 1000$ are Type II and III

One of the important goals of our visual investigation was to build up a large enough sample to enable us to determine which one of the four types of local Typical eddy wall interaction was most common. We analyzed 10 rolls of film (10 runs at $R_\theta \cong 1000$ and found that it is either Type II or Type III interactions that are the most common. The problem with getting a more definitive answer is that we could not separate marked fluid once it was lifted (since it is all white oil droplets) to determine a) if it originated from the sublayer, b) if some of it entered the evolving Typical eddy or not, except for some occasions where concentration gradients were accidently present. Although observations when mother nature permitted were enough to understand the presence of the phenomena, we could not build a statistical sample on this basis. This state of affairs, combined with the desire to see whether or not the situation was different in the cases when streaks formed upstream, has led to the multiple color dye water tunnel experiments described below. As a result we have not counted the number representative of each catagory. However, we can also say that Type IV events are quite rare at $R_\theta \cong 1000$.

2.1.3 Multiple color LIF experiments in water boundary layer

Our existing 20 ft x 3 ft x .5 ft water tunnel was modified to enable different fluorescent dyes to be introduced from various streamwise positions along the wall. James Chang is the student doing this experiment. Using laser induced fluorescence (LIF), we are able to determine where specific fluid comes from and where it goes.

2.1.3.1 Three dye experiments with a single laser sheet

Using a sublayer slit and two holes placed upstream of the slit to introduce different color dyes, we could observe the Typical eddy/wall interaction in a laser sheet perpendicular to the wall and parallel to the flow in detail. This shed light on the region of the boundary layer from which the Typical eddy had come (which we can correlate with the eddies convection velocity and the relative positions of the large scale motions), and enabled us to clearly see wall fluid lifted up and ingested or not ingested into the ring (needed to confirm the hypothesis that ring instability was directly correlated with the ingestion of sublayer fluid). It also enabled us to more clearly witness the tightening of the lower part of the Typical eddy due to inviscid stretching as it came near to the wall in a thin viscous sublayer. This technique was originally going to be used to determine the percentage of each of the original type I - type IV interactions. However, with the understanding of the additional types, we expanded the technique to include the plan view.

2.1.3.2 Two view/two dye experiments

Using a laser sheet normal to the wall and by flood illuminating the slit marked sublayer, and introducing dye upstream into the outer region, we obtained results that will enable us to answer the questions about the percentage of the time the various types of interactions occur. Analysis of this data is still being done.

2.1.3.3 Dual slit, three dye, two view experiments

We are currently setting up a dual slit, three dye, laser/flood illuminated experiment. These experiments should be completed during the current contract period, with analysis later. It will enable us to isolate those steaks that are formed by the Typical eddy in view in the laser sheet, from streaks formed upstream which are just fossil remnants of stable streaks that would otherwise confuse our picture. We will use the first slit to define the start of the long streaks, and just as the lifted wall layer fluid begins to lift up, we will have a second slit with a third color dye to mark the presence of the pockets forming between the streak pair (if conditions are right for this to happen), and give details in the local interaction zone. This experiment will be able to answer the questions about the connection between long streak formation and the Typical eddy. We are interested not only in details the eddy that produces stable vs. unstable streaks, but also about the questions of whether the eddy must be in stable condition and very coherent, and whether other motions in the boundary layer, on other scales, can also produce streaks.

We are also interested to examine these films for evidence of lifted hairpins undergoing the pinch-off and formation of new vortex rings.

2.1.4 Vortex ring/moving wall simulations in water and kerosene

The vortex ring/moving wall experiments are being performed to continue our investigation of the influence of the various parameters in determining the strength of the interaction. Daniel Chu is the student carrying out the experiments.

2.1.4.1 Discovery that vortex ring/wall interaction produces long streaks

As discussed above, we have discovered that over a certain range of parameters the vortex ring/moving wall interaction can produce long streaks. Only the lower speed rings can do this, and in our analogy, this means that only the higher speed Typical eddies of the boundary layer will produce a pair of long streaks before they create a pocket. There is an exception for high speed rings moving approximately parallel to the wall. As mentioned above, these observation have been made in the fully turbulent boundary layer. However, they were first observed in these simulation experiments.

Our observations in both the boundary layer and in the simulation experiments are admittedly incomplete, but we have a growing feeling that the streak spacing is primarily due to Typical eddies in the boundary layer. If it was not, and all other eddies contributed, there would be a uniform distribution of streaks resulting in essentially zero spacing, rather than the observed spacing of 100 wall layer units. In our proposed work, two different experiments are described to determine the answer.

2.1.4.2 Discovery that lifted hairpins 'pinch off' into vortex rings

Under a certain limited set of conditions -- shallow wallward angle and $U_r > .6U_w$ --we have observed that the hairpin that lifts out of the pocket can undergo a rearrangement in which the legs come close together and diffusion processes take over, resulting in a vortex ring, with a new hairpin left behind. This is one mechanism for the regeneration process, in which new vortex ring-like Typical eddies can form in the turbulent boundary layer.

2.1.4.3 Vorticity measurements using the photochromic technique

After several attempts to construct a static beam splitting device that will take a single laser beam and divide it into two sets of 25 beams that will cross to make a grid, we have succeeded in producing a prototype, which has been specially silvered, and used to produce a rake of ultraviolet lines. When passed into kerosene doped with our photochromic chemical, we have obtained our first high resolution lines into a fluid. We are in the process of having a pair of devices made, and anticipate obtaining our first test results in solid body rotation in a cylinder, and then move on to tests measuring the vorticity in a Stokes layer created on our impulsively started moving belt; then to measurement of transverse vorticity in a vortex ring; and then to measurements of the streamwise vorticity in the streak produced by the vortex ring/wall interaction. In the proposed work, we want to measure the vorticity in the coherent motions in a turbulent boundary layer.

2.1.5 Modifications to the production process

Our knowledge of the elements of the production process has led us to examine how it changes in the presence of riblets in our simulation, and to determine how the presence of LEBU's affect the rate of production in a flow where the net drag has been lowered. Andreas Oldeweme is the student working on the moving plate/riblet experiments. Dr. Nasser Rashidnia contributed to the pocket counting with/without LEBU's.

2.1.5.1 Vortex ring/moving plate interaction

Modifications that riblets can make to the turbulence production process are being studied to see what the most sensitive aspects of the process are. A 16 ft x 2 ft x 1.8 ft tank has been built which can use kerosene for future photochromic experiments, and has been outfitted with a moving plate that can be accelerated from rest to a constant speed (and decelerated to rest again). Using this facility we first reproduced the interactions found using the moving belt, and have recently started to examine the changes found when the vortex rings interact with the riblet covered wall.

Our riblet surfaces are made by machining the desired geometry into a roller, and then impressing the riblets into sheets of wax. In this way, riblet plates can be made inexpensively, allowing us to investigate the effects of geometry on the interactions.

Our early results using triangular riblets with spacing and height at the optimum as defined by Walsh 1982 i.e., $h^+ = 11$, $s^+ = 22$, showed that the riblets did not affect the formation of a long streak pair. On the contrary, the pair developed as usual with the exception that it was spaced 10% further apart. We also observed that the pocket that was created was also larger and seemed to be more pronounced. Interestingly, the presence of the riblets inhibited the bifurcation under the same conditions that led to catastrophic breakdown on a smooth plate. Since the experimental facility has only been running for a few weeks, we are looking forward to an insightful set of experiments.

2.1.5.2 Effects of LEBU's on the frequency of bursting

We have also investigated the effect of LEBU's on the frequency of occurrence of pockets at a position where the net drag is reduced by about 5%. We found that the mean frequency of occurrence of the pockets decreased when scaled on outer layer variables. This is consistent with our expectations. An interesting fact emerged from these movies.

There was less of an indication of the presence of the long streaky structure. This suggests that the large-scale wallward motions were not as strong, and therefore did not bring as many Typical eddies into close enough proximity to cause an interaction.

2.2 Implications for control of boundary layer turbulence

If we hypothesize that Typical eddies are the major causative factor in the creation of both the long streaks and the pockets, and if the breakup of the long streaks and the liftup of the fluid in the pocket and its ingestion into the ring and ring breakdown are the major causes of turbulence energy production, we have the basis for a number of controls on the turbulence energy production process. The effectiveness of the controls suggested by the vortex ring/wall experiments depends upon a) whether the distribution of vorticity in the Typical eddies is similar to that in the artificially generated vortex rings, b) the distribution of vorticity in the Stokes layer is similar to that in the sublayer c) the sensitivity of the vortex rings/Stokes layer interaction to changes in δ/D, U_r/U_w, and angle of incidence, is similar to the sensitivity of the Typical eddy/sublayer interaction. We will propose to study some of these sensitivities in the simulations, and to obtain actual measurements of the vorticity distributions of the Typical eddies, and vortex rings.

2.2.1 Example of controls to reduce drag

Figure 1 shows the streak/ring stability situation with the abscissa also indicating the situation as it would appear in the boundary layer. It is for a constant angle of incidence. The lines on the map indicate the stability boundaries which are quite sharp. This is true for both the ring and the streak stability boundaries. If the boundaries are as sharp in the turbulent boundary layer we will have important opportunities for control. For example, by changing the eddy size, or the sublayer thickness, or the angle of incidence (weakening the large eddies) by a very small amount, we can move an eddy that is at a point on the unstable side of either the streak or the eddy stability boundary, or both, across the stability boundaries to make its interactions stable. Other ideas involve learning how to a) reduce the frequency of the Typical eddies--by inhibiting their formation or by causing them to dissipate faster; b) prevent the Typical eddies from getting close enough to the wall to interact; c) thicken the wall layer so that the interactions are weakened; d) change the vorticity distribution within the eddies so that the stability maps change, shifting to more stable positions. Many others come to mind, but until we determine the sensitivity to the parameters, the most efficient path to control will not be clear.

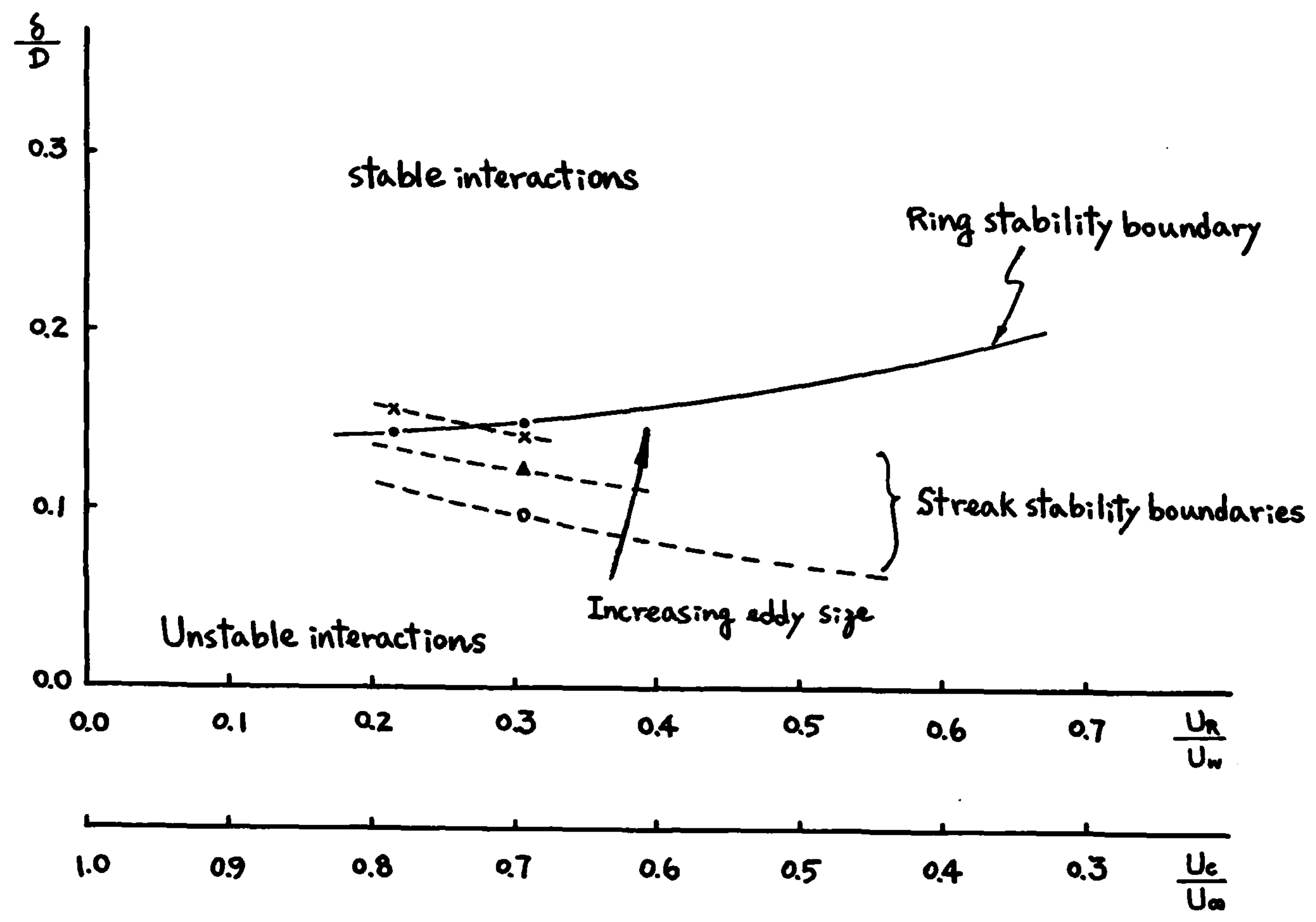

Fig. 1 Stability of Wall Region Interactions

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